TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 1027

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By W. Bleeker

Meteorologische Zeitschrift, September 1932

Washington
August 1942

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THE FORMATION OF ICE ON AIRCRAFT*

By W. Bleeker

The phenomenon accompanying the formation of ice on aircraft has been fairly frequently discussed. The consequences of ice formation have been briefly analyzed in an article by K. Wegener (reference 1), but a definite physical solution of the problem has not been reached up to the present.

Most of the authors are agreed that subcooled water droplets play a prominent part, but they fail to specify the exact manner in which this occurs. As an illustration of one fairly contestable theory to be found in American periodicals (reference 2) the following is quoted:

"Owing to the small radius of curvature of the cloud elements the inwardly directed resultant of the surface tension causes a considerable pressure rise in these droplets, which in water, as experience indicates, signifies a lowering of the freezing point; hence the freezing of the water droplets can occur only at lower temperature. The sometimes very great supercooling of the cloud elements is explained in this manner. On striking the aircraft the pressure increase is destroyed; the droplets freeze immediately and ice forms on the aircraft."

In the first place, this does not explain the supercooling at all. Water can be supercooled to below -10° C in a glass in the laboratory. In the second place the qualitatively well-sounding explanation of the supercooling fails utterly in a quantitative study, as is seen from the following:

The formula for the positive pressure of the surface tension in a drop reads

$$\Pi = \frac{2H}{R} \text{ grams per square centimeter} \qquad (1)$$

*"Einige Bemerkungen über Eisansatz an Flugzeugen." Meteorologische Zeitschrift, September 1932, pp. 349–354.

H capillary constant of water (7.4 mg/mm)

R radius of droplet

From Clapeyron's formula

$$\frac{dp}{dT} = \frac{r}{T(V_1 - V_2)} \tag{2}$$

where

p pressure

T temperature

r heat of crystallization

$V_1 - V_2$ difference in specific volume of water and ice

It is readily seen that a pressure rise of no less than 125 kilograms per square centimeter is required to lower the freezing point by 1° C. In the case in question the reduction is less than 0.001° C.

The falseness of this theory is evident from these figures.

Dr. Kopp pointed out an entirely different possibility of solution of the ice accretion problem (reference 2). According to him, the supersaturation of water vapor relative to ice is to be of great importance. Experience indicates that the pressure of water vapor on saturation relative to water is greater for the same temperature at saturation relative to ice. According to him, and others sublimation should occur on an ice-coated airplane in an atmosphere saturated relative to water.

This assertion, however, embodies the assumption that the ice coating on the airplane is and remains dry, which in our opinion is far from being the case. Even if it were true, is the supersaturation then heavy enough to explain the formation of, say, a 1-centimeter ice coating within 10 minutes? At -5° C the above-mentioned vapor-pressure difference is 0.1 millimeter of mercury. This means that 0.1 gram of water per cubic meter of air can sublimate. At 50 meters per second flying speed a volume of 3 cubic meters per square centimeter is covered in 10 minutes. So at the most, only 4 millimeters of ice could form on the aircraft. But this is not the case at all because the greater part of the air does not touch the airplane parts. So, at the most, only 4 millimeters of ice could form on the aircraft. It seems as if this explanation fails also quantitatively, as pointed out elsewhere (reference 4). Of course, the possibility of great supersaturation in the clouds can also be pointed out. Kopp asserts that he found this supersaturation (reference 5); we believe that he unduly ignored the dynamic causes of the ascent of the cumuli clouds. But even a 1000-percent supersaturation does not seem to be sufficient.

An attempt was made to find an interpretation of this puzzling phenomenon in some other manner. The author is in agreement with the American concept in this respect, that the mechanical impact of subcooled droplets with the airplane is followed by freezing. But the subcooling should be regarded only as a kind of inertia which, as we know, is canceled on collision. Owing to the high value of the crystallization heat a droplet striking the airplane is only partly frozen. A droplet of -5° C temperature becomes 15/16 part ice; the resulting ice-water mixture has a temperature of 0° C. The air (-5°) flowing past the mixture cools it off further. Which is the important cooling factor? – The water-vapor pressure over the water-ice mixture of 0° C is much greater and not lower, as Kopp believes, than the water vapor pressure of the surrounding air of -5° C. This water-vapor difference enables a considerable evaporation of the water by the marked ventilation. So much heat is withdrawn from the water that a large portion freezes.

The importance of the vapor pressure difference and the high-air speed is apparent from Trabert's evaporation formula (reference 6).

$$V = C\left(1 + \frac{t}{273}\right)w^{1/2}(E - e)\,\frac{760}{B} \tag{3}$$

where

V evaporated quantity in millimeters per time unit (day)

C constant

t temperature of water

w wind velocity

E water-vapor pressure of the surface, millimeters of mercury

e water-vapor pressure of air in millimeters of mercury

B air pressure in millimeters of mercury

From Braak's figures (reference 7) computed for India $C(1 + t/273)$ is computed at 0.59 for 0° C temperature.

The exponent of w, 1/2 established for low speeds, is somewhat greater (0.58) for greater velocities, as is known from heat engineering. The value 1/2 was assumed in our subsequent arguments.

Owing to the very small variations of B in practice the value 720 millimeters of mercury was assumed. By substitution of this figure in Trabert's formula the time within which a quantity of water freezes as a result of the ventilation, can be computed. The heat of evaporation at 0° C is around 600 calories per gram, the heat of crystallization, 80 calories per gram of the water not turned to ice 12 percent must evaporate in order that the remaining 88 percent can freeze.

To illustrate: Visualize a water droplet of 0° C pulled through air of lower temperature at airplane speed of, let us say, 50 meters per second. A droplet of 10^{-3} centimeter radius turns to ice in about 7 seconds according to Trabert's formula. This does not even take into account that the saturation pressure by the great curvature is greater than above a flat surface. Assume further that the relative moisture in the clouds is 100 percent, that the droplet maintains its spherical shape and its radius does not vary during the evaporation. If it were possible to figure exactly with all these factors, the time would be even less.

For the relationship of the "icing time," Γ to drop radius R we find

$$\Gamma = KR \tag{4}$$

K indicating a value largely defined by the vapor pressure, that is, the temperature and relative moisture of air. At lower temperatures and in lower relative moisture K will be smaller; hence the water droplet will freeze quickly in cold, dry air. The proportionality of Γ and R in (4) is obvious since the ratio content : surface is decisive. Larger droplets offer larger surfaces for the evaporation (in ratio to R^2), but the 12 percent which must be evaporated before complete freezing occurs, vary with R^3. Smaller droplets therefore freeze more quickly.

Now to a practical experiment: The cloud elements strike the airplane and are then carried along at a speed of 50 meters per second. But the "time of icing," will be greater than on the previously computed spherical droplet, for the ventilation is not possible on the part adhering to the airplane. However, the resulting difference is at the most 2, but probably much less, because the ratio content/surface is most unfavorable at the spherical shape. The magnitude of this ratio will depend upon the characteristics of the airplane parts (cohesion relative to water) but that only in the first instants before a thin ice coating has formed. Experience indicates that no difference exists between wooden or metal aircraft at icing. Rubbing the airplane wing with oil does not make the ice accretion any less according to laboratory tests made at Amsterdam (reference 8). It can be assumed therefore that the droplets adhere on impact, while the ratio content : surface can never be more than twice as bad as on the droplet in spherical form, before it struck the airplane.

The concept "icing time" maintains its importance in practice.

If, by large drop radius, high relative moisture and near freezing temperature, the "icing time" is long, the drops have sufficient time to flow together and blow away from the airplane. But, if the "icing time" is so short that, at the instant one droplet is frozen, another one hits the airplane at about the same place, the ice accretion will be heavy.

Probably many difficulties can be explained by means of the concept "icing time." There is the stormy ice accretion observed many times even in horizontal flight, which causes so much more astonishment because externally nothing appears to change. Flying through fog of −0.1° C and 100 percent relative moisture into other levels with 92 percent moisture, for instance, indicates a change of about 0.4 millimeter of mercury in vapor pressure, which is great enough to freeze a drop of water (10^{-3} cm radius) in less than 25 seconds.

It also affords an explanation for the appearance of ice accretion above the freezing point, as observed at times in the United States. It requires a relatively dry fog. Naturally it should not be forgotten that, in a hygroscopic fog where drops at a relative moisture of 92 percent can very well be in equilibrium with the water vapor, this effect cannot occur. But it can occur when drops of water fall silently (for instance, in an inversion) and so penetrate into dry air.

The relation of icing time to ventilation also affords an explanation of the peculiar mushroomlike growth of ice on the leading edges of aircraft wings, as pointed out in U.S. publications (fig. 1)(reference 9). The speed is highest at A and B, where the icing time is shortest; hence a thicker ice coating is deposited. The success of the recommended remedy to coat the wing with syrup, is largely due to the lower vapor pressure.

According to Raoult the depression of the saturation pressure of a solution is

$$E = e \frac{\frac{p}{M}}{\frac{p}{M} + \frac{p'}{M'}}$$

where

e saturation pressure of the pure dissolving agent

p mass of dissolved body

p' mass of dissolving medium

M molecular weight of dissolved body

M' molecular weight of dissolving agent

In 100 grams of water, 180 grams of cane sugar is dissolvable. Coating the parts of an airplane with this solution actually affords saturation only at the beginning; but, then, E = 0.5. This means that at 100 percent relative moisture of the surrounding air no icing can occur up to about -1.6° C (lowering of freezing point); but it also means that at lower temperature the "icing period" is substantially greater, so that the water blows off from the airplane. After some time, however, the medium becomes less effective because of the dilution. Hence in our opinion not only the impossibility of the drops to freeze between 0 and -1.6° C, but also the marked increase of the "icing period" for temperature below -1.6° C are of great importance.

It might be argued that too much emphasis is laid on evaporation in the foregoing. The cooling certainly supervenes through the air flowing simply past, but that makes the possibility for ice deposition still easier. On top of that, it is generally conceded that in all such processes evaporation plays the major part.

Another question is: Is it possible to interpret a deposit of 1-centimeter thickness in 10 minutes only by "interception" of drops? Noth (reference 11) has pointed out that the icing is proportional to the water content, the relative speed, the time, and the sine of the angle of impact. Several other factors are also involved, as has been shown. But the water content plays a very important part. According to measurements by Köhler the number of water droplets per cubic centimeter in a cloud range between 250 to 400. In winter the absolute maximum of the drop radius lies at 0.8×10^{-3} centimeter. Drops larger than 1.6×10^{-3} centimeter are scarcely found in clouds and fog. Assuming that 330 drops of a radius of 10^{-3} centimeter per cubic centimeter exist, and all the drops are caught in the space crossed by the airplane, an ice deposit of 5.5 centimeters is possible under maximum conditions favorable to icing.

Of course the exact number of drops striking the airplane cannot be accurately calculated, but a general idea may be obtained from the following:

For an ideal, incompressible fluid we plot the theoretical streamlines about a circle of 25 centimeters radius on a flow which at infinity moves at 50 meters per second speed parallel to the X axis. This flow follows the complex function.

$$w = \frac{UR^2}{z} - U z \tag{5}$$

where

U speed at infinity

R radius of circle

After substitution of U and R the equation for the streamlines reads

$$y \left(\frac{625}{x^2 + y^2} - 1 \right) = \lambda \tag{6}$$

with λ a parameter different for each streamline.

From this (6) the streamlines are easily computed. Then, if a water particle is carried along the stream-line, it is subjected in every point to a force perpendicular to its direction of motion by reason of the curvature of its path. It is "centrifugated out of its path." Hence the water droplets follow an entirely different path from the streamlines of the air.

The radius of curvature at each point can be computed. It is:

$$\rho = \frac{(x^2 + y^2)\{390400 - 1250\,(x^2 - y^2) + (x^2 + y^2)^2\}^{3/2}}{1250\,y\,\{390400 + 1250\,(x^2 + y^2) + (y^2 - 3x^2)(x^2 + y^2)\}} \tag{7}$$

Since the tangential velocity itself can be calculated, the centrifugal force v^2/ρ on a drop can be obtained. This was made for many points of the streamlines shown in figure 2, on the basis $v = U = 5000$ centimeters per second tangential velocity for simplicity. The centrifugal accelerations even at great distance from the circle are much higher than g. Stokes' law, which still holds for drops of 10^{-3} centimeter and can therefore be used to compute the speed of the drops perpendicular to the stream-lines, was applied to every $2\frac{1}{2}$ centimeters in the vicinity of the circle. The calculation defining the amount by which the droplet moves away from its original streamline was made on the basis of maximum curvature radius (that is, smallest centrifugal acceleration), but for compensation with the maximum Stokes' velocity:

$$u = 1.26 \times 10^3 \times b \times r^2$$

$$b = \text{acceleration } \frac{v^2}{\rho}$$

$$r = \text{radius of droplet}$$

The calculation is very tedious as each streamline requires a new constant, part of which must be plotted, and then the vertical motion determined again. Figure 2 indicates how approximately a particle, originally moving in streamline I, changes its path because of the centrifugal forces. It ultimately moves in streamline II at point A and is then removed again from the circle, since at A the curvature radius changes sign. The second water droplet, originally on II and which can be traced as far as B, is intercepted by the circle.

From this it can be concluded that - roughly estimated - certainly more than a tenth of the number of droplets in the space crossed by the circle, are "caught."

While the foregoing remarks were merely intended to give an idea of the order of magnitude, the favorable results in this instance justify the statement that it is not unlikely that the "interception" of the droplets rather than sublimation plays the most important part on ice accretion.

Translation by J. Vanier,
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REFERENCES

1. Wegener, K: Die Vereisung von Luftfahrzeugen. Meteorol. Zeitschr. 47, 140.

2. Carroll, Thomas, and MacAvoy, William H.: The Formation of Ice Upon Airplanes in Flight. Rep. No. 313, NACA, 1929.
   Andrus, C. G.: The Problem of Combating Ice-Accumulation. Aviation, April 1928.

3. Kopp, W.: Danger of Ice Formation on Airplanes. T.M. No. 499, NACA, 1929.
Koppe, Heinrich: Von den Gefahren des Luftmeeres. Z.F.M., vol. 20, July 31, 1929, pp. 367-375.
Robitzsch, M.: Über die Vereisung von Luftfahrzeugen. Beitr. z. Phys. d. fr. Atm. 18, 235.

4. Humphreys, W. J.: Supersaturation and Icing of Airplanes. Monthly Weather Review, 58, 245.

5. Kopp, W.: Über die Möglichkeit mit den Gewöhnlichen Aerologischen Hilfsmitteln die Übersättigung der Wolkenluft zu Bestimmen. Beitr. z. Phys. d. fr. Atm. 16, 173, 1930.

6. Trabert, W.: Meteorol. Zeitschr. 36, 61, 1896.

7. Braak, C.: Het Klimaat van Nederlandsch-Indië. Verhandeling Nr. 8. Deel I, p. 390.

8. Rijksstudiedienst voor luchtvaart. Eenige Proeven over Ijsafzetting. Rapport A 238.

9. Carroll, Thomas, and MacAvoy, William H.: (loc. cit.)
Siehe auch:
Heitmanek, O.: Die Eisbildung am Flugzeug Während des Fluges. Revue Aëronautique Internationale 1931-1932.

10. Carroll, Thomas, and MacAvoy, William H.: (loc. cit.)
Andrus, C. G.: Meteorological Notes on the Formation of Ice on Aircraft. Monthly Weather Review. Jan. 1930, p.23.

11. Noth, H.: Die Vereisungsgefahr bei Flugzeugen. Die Arbeiten des Preussischen Aeronautischen Observatoriums. Bd. 16, G. 1-12.

Additional literature available at the time this article was completed:

Van Everdingen, E.: IJs en Ijzel in Het eind van 1927. Hemel en Dampkring 26, 33.

Breitfuss, L.: Die Nobile's Nordpolexpedition mit dem Luftschiff. Petermanns Mitteilungen 75, 1.

Peppler, W.: Reif und Eisbildung in der Freien Atmosphäre. Beitr. z. Phys. d. fr. Atm. 10, 38.

Steiner, O.: Vereisung von Flugzeugen. Meteorol. Zeitschr. 47, 335.

Lohr, A.: Ergebnisse der Hamburger Flugzeugaufstiege der Deutschen Seewarte. Aus dem Archiv der Deutschen Seewarte, 49, Nr. 10.

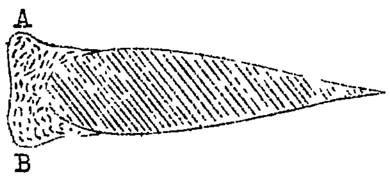

Figure 1

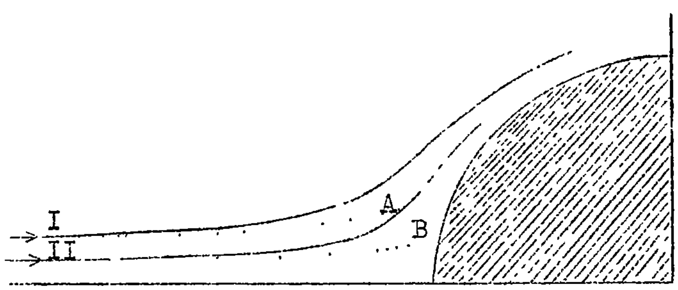

Figure 2